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Performance optimization of a two-stage semiconductor thermoelectric-generator

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Abstract

A model of a two-stage semiconductor thermoelectric-generator with external heat-transfer is built. Performance of the generator, assuming Newton's heat-transfer law applies, is analyzed using a combination of finite-time thermodynamics and non-equilibrium thermodynamics. The analytical equations about the power output versus the working electrical current, and the thermal efficiency versus working electrical-current are derived. For a fixed total heat-transfer surface-area for two heat-exchangers, the ratio of heat-transfer surface-area of the high-temperature side heat-exchanger to the total heat-transfer surface-area of the heat-exchangers is optimized for maximizing the power output and the thermal efficiency of the thermoelectric-generator. For a fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the top stage to the total number of thermoelectric elements is also optimized for maximizing both the power output and the thermal efficiency of the thermoelectric-generator. The effects of design factors on the performance are analyzed.

Keywords: Two-stage semiconductor thermoelectric-generator; Finite-time thermodynamics; Non-equilibrium thermodynamics; Optimization

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1. Introduction

Semiconductor thermoelectric power-generation, based on the Seebeck effect, has very interesting capabilities with respect to conventional power-generation systems [1–4]. The absence of moving components results in an increase of reliability, a reduction of maintenance, and an increase of system life; the modularity allows for the application in a wide-scale range without significant losses in performance; the absence of a working fluid avoids environmentally dangerous leakages; and the noise reduction appears also to be an important feature. Thermoelectric generators have been used in military, aerospace, instrument, industrial and commercial products, as a power-generation device for specific purposes. Many researchers have been concerned about the physical properties of thermoelectric materials and the manufacturing technique of thermoelectric modules [5–7]. In addition to the improvement of the thermoelectric materials and modules, the system analysis (and optimization) of a thermoelectric generator is equally important in designing a high-performance thermoelectric-generator.

In general, conventional non-equilibrium thermodynamics [1,8,9] is used to analyze the performance of single-stage one- or multiple-element thermoelectric-generators [10–18]. Due to the performance limits of thermoelectric materials, thermoelectric-generators of two stages or more should be applied to improve the level of thermodynamic performance. Zhou [19] analyzed and optimized the performance of two-stage thermoelectric-generators. All of those were performed by using the conventional non-equilibrium thermodynamics without considering the external losses.

The theory of finite-time thermodynamics or entropy-generation minimization [20–30] is a powerful tool for the performance analysis and optimization of practical thermodynamic processes and devices. Some authors have investigated the performances of thermoelectric-generators using a combination of finite-time thermodynamics and non-equilibrium thermodynamics [31–48]. Sun et al. [31,32], Gordon [33], Wu [34–36], Agrawal et al. [37], Chen [38–40], Xuan et al. [41,42] and Nuwayhid et al. [43] analyzed the effect of the finite-rate heat-transfer between the thermoelectric device and its external heat-reservoirs on the performance of single-element single-stage thermoelectric-generators. Chen et al. [44], Chen et al. [45–47], and Crane et al. [48] investigated the characteristics of single-stage multi-element thermoelectric-generators with the irreversibility of finite-rate heat-transfer, Joulean heat inside the thermoelectric device, and the heat leak through the thermoelectric couple leg. There is no similar study for the performance analysis and optimization of two-stage thermoelectric generators.

On the basis of the exo-reversible model of two-stage thermoelectric-refrigerators [19], a model of two-stage semiconductor thermoelectric-generators, with external heat-transfer, is built. The performance of the generator obeying Newton's heat-transfer law is analyzed using the combination of finite-time thermodynamics and non-equilibrium thermodynamics. The analytical formulae about power output versus working electrical-current, and the thermal efficiency versus working electric-current are derived. For the fixed total heat-transfer surface-area of the two heat-exchangers, the ratio of heat-transfer surface-area of the

high-temperature side heat-exchanger to the total heat-transfer surface-area of the heat-exchangers is optimized for maximizing the power output and the thermal efficiency of the thermoelectric generator. For the fixed total number of thermoelectric elements, the ratio of the number of thermoelectric elements of the top stage to the total number of thermoelectric elements is also optimized in order to maximize the power output and the thermal efficiency of the thermoelectric generator. The effects of design factors on the performance are analyzed. The optimum distribution of heat conductance or heat-transfer surface-area for conventional power and refrigeration plants was first advanced by Bejan [49–53]. Similar studies for two-stage Carnot heat-engines were performed by Chen et al. [54,55].

2. Two-stage thermoelectric-generator

A schematic diagram of a two-stage thermoelectric generator with the losses of external heat-resistance, Joule heat inside the thermoelectric device, and the heat leak through the thermoelectric couple leg is shown in Fig. 1. The generator consisted of a top stage with m pairs of thermoelectric elements and a bottom stage with n pairs of thermoelectric elements. The total number of pairs of the refrigerator is M, i.e. $M = m + n$. Each element is composed of p-type and n-type semiconductor legs. The thermoelectric power-generation element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction–reservoir contacts and the junction between the two stages. The internal irreversibility is caused by Joulean electrical-resistive loss and heat-conduction loss through the semiconductor between the hot and cold junctions. The Joulean loss generates internal heat I^2R, where R is the total internal electrical-resistance of the

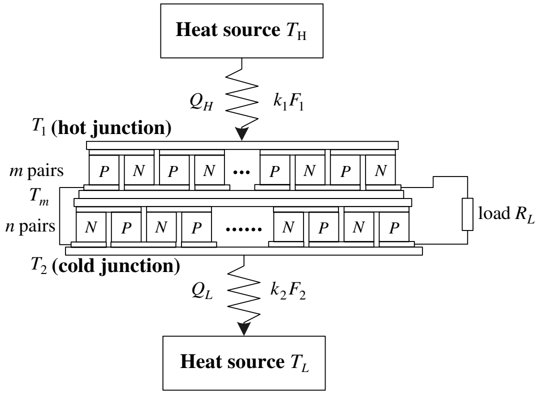

Fig. 1. A schematic diagram of a two-stage semiconductor thermoelectric-generator with internal and external irreversibilities.

semiconductor couple and I is the electrical current generating through the semiconductor couple. The conduction heat losses are $K(T_1 - T_m)$ for the top stage and $K(T_m - T_2)$ for the bottom stage, respectively, where K is the thermal conductance of the semiconductor couple, T_1 is the hot-junction temperature, T_2 is the cold-junction temperature, and T_m is the temperature of the junction between the two stages. Finite-rate heat-transfers, i.e., the temperature differences $(T_{\mathrm{H}} - T_1)$ and $(T_2 - T_{\mathrm{L}})$, where T_{H} and T_{L} are the temperatures of the heat source and heat sink, respectively, cause the external irreversibility. For the generator, the rate of heat transfer at the hot junction is Q_{H}, and the rate of heat transfer at the cold junction is Q_{L}. The power output of the generator is P. The electrical resistance of the external load is R_{L}. Assume that the two heat-exchangers between the hot and cold junctions of the thermoelectric generator and their respective reservoirs are for counter flows, and the heat conductances (i.e., product of heat-transfer coefficient and heat-transfer area) of the heat-exchangers are k_1F_1 and k_2F_2, respectively, where k_1, k_2, F_1, and F_2 are heat-transfer coefficients and heat-transfer surface-areas of the two heat-exchangers, respectively.

Assuming that the heat-transfers between the hot and cold junctions of the thermoelectric generator and their respective reservoirs obey Newton's law, then

$$Q_{\mathrm{H}} = k_1F_1(T_{\mathrm{H}} - T_1), \tag{1}$$

$$Q_{\mathrm{L}} = k_2F_2(T_2 - T_{\mathrm{L}}). \tag{2}$$

The following equations apply at the three junctions:

$$Q_{\mathrm{H}} = m\alpha IT_1 - mI^2R/2 + mK(T_1 - T_m), \tag{3}$$

$$Q_m = m\alpha IT_m + mI^2R/2 + mK(T_1 - T_m), \tag{4}$$

$$Q_m = n\alpha IT_m - nI^2R/2 + nK(T_m - T_2), \tag{5}$$

$$Q_{\mathrm{L}} = n\alpha IT_2 + nI^2R/2 + nK(T_m - T_2), \tag{6}$$

where $\alpha = \alpha_{\mathrm{p}} - \alpha_{\mathrm{n}}$, α_{p} and α_{n} are the Seebeck coefficients of the p-and n-type semiconductor legs for each thermoelectric power-generation element, and Q_m is the rate of heat flow between the two stages in the system.

3. Power output and thermal efficiency

Combining Eqs. (4) and (5) gives

$$T_m = \frac{(m+n)I^2R/2 + mKT_1 + nKT_2}{\alpha I(n-m) + K(m+n)}. \tag{7}$$

The heat-balance conditions give

$$Q_H = m[\alpha I T_1 - I^2 R/2 + K(T_1 - T_m)] = k_1 F_1 (T_H - T_1), \tag{8}$$

$$Q_L = n[\alpha I T_2 + I^2 R/2 + K(T_m - T_2)] = k_2 F_2 (T_2 - T_L). \tag{9}$$

Substituting Eq. (7) into Eqs. (8) and (9) and combining these equations yields

$$\begin{aligned} T_1 = {} & \big(\{[\alpha I(n-m) + K(m+n)](k_1 F_1 T_H + m I^2 R/2) + (m+n) m K I^2 R/2\} \\ & \times (k_2 F_2 + nK - n\alpha I) + nK^2 (m k_2 F_2 T_L - n k_1 F_1 T_H)\big) \\ & /([\alpha I(n-m) + K(m+n)](k_1 F_1 + mK + m\alpha I)(k_2 F_2 + nK - n\alpha I) - (nK)^2 \\ & \times (k_1 F_1 + mK + m\alpha I) - (mK)^2 (k_2 F_2 + nK - n\alpha I)), \end{aligned} \tag{10}$$

$$\begin{aligned} T_2 = {} & \big(\{[\alpha I(n-m) + K(m+n)](k_2 F_2 T_L + n I^2 R/2) + (m+n) n K I^2 R/2\} \\ & \times (k_1 F_1 + mK + m\alpha I) - mK^2 (m k_2 F_2 T_L - n k_1 F_1 T_H)\big) \\ & /([\alpha I(n-m) + K(m+n)](k_1 F_1 + mK + m\alpha I)(k_2 F_2 + nK - n\alpha I) \\ & - (nK)^2 (k_1 F_1 + mK + m\alpha I) - (mK)^2 (k_2 F_2 + nK - n\alpha I)). \end{aligned} \tag{11}$$

Substituting Eqs. (10) and (11) into Eqs. (1) and (2) yields

$$\begin{aligned} Q_H = {} & (m k_1 F_1 \{[\alpha I(n-m) + K(m+n)](k_2 F_2 + nK - n\alpha I)(\alpha I T_H - 0.5 I^2 R + K T_H). \\ & - 0.5(m+n) K I^2 R (k_2 F_2 + nK - n\alpha I) - (nK)^2 (\alpha I + K) T_H \\ & - K^2 [k_2 F_2 (m T_H + n T_L) + mn(K - \alpha I) T_H]\}\big) \\ & /([\alpha I(n-m) + K(m+n)](k_1 F_1 + mK + m\alpha I)(k_2 F_2 + nK - n\alpha I) \\ & - (nK)^2 (k_1 F_1 + mK + m\alpha I) - (mK)^2 (k_2 F_2 + nK - n\alpha I)), \end{aligned} \tag{12}$$

$$\begin{aligned} Q_L = {} & \big(n k_2 F_2 \{[\alpha I(n-m) + K(m+n)](k_1 F_1 + mK + m\alpha I)(\alpha I T_L + 0.5 I^2 R - K T_L) \\ & + 0.5(m+n) K I^2 R (k_1 F_1 + m\alpha I + mK) + (mK)^2 (K - \alpha I) T_L \\ & + K^2 [k_1 F_1 (m T_H + n T_L) + mn(K + \alpha I) T_L]\}\big) \\ & /([\alpha I(n-m) + K(m+n)](k_1 F_1 + mK + m\alpha I)(k_2 F_2 + nK - n\alpha I) \\ & - (nK)^2 (k_1 F_1 + mK + m\alpha I) - (mK)^2 (k_2 F_2 + nK - n\alpha I)). \end{aligned} \tag{13}$$

The power output (P) and the thermal efficiency (η) of the generator are

$$P = Q_H - Q_L, \tag{14}$$

$$\eta = Q_H / P. \tag{15}$$

One can derive the power output and the thermal efficiency of the generator as follows

$$
\begin{aligned}
P &= Q_{\mathrm{H}} - Q_{\mathrm{L}} \\
&= (\{[\alpha I(n-m) + K(m+n)][(mk_1F_1k_2F_2 + mnKk_1F_1 - mnk_1F_1\alpha I) \\
&\quad \times (KT_{\mathrm{H}} + \alpha IT_{\mathrm{H}} - 0.5I^2R) - (nk_1F_1k_2F_2 + mnKk_2F_2 + mnk_2F_2\alpha I) \\
&\quad \times (\alpha IT_{\mathrm{L}} - KT_{\mathrm{L}} + 0.5I^2R)] + 0.5(m+n)KR[(n-m)k_1F_1k_2F_2 \\
&\quad + mnK(k_1F_1 - k_2F_2) - mn(k_1F_1 - k_2F_2)\alpha I]I^2 \\
&\quad - (n-m)(mT_{\mathrm{H}} + nT_{\mathrm{L}})k_1F_1k_2F_2K^2 + mn(n-m)K^2(k_1F_1T_{\mathrm{H}} - k_2F_2T_{\mathrm{L}})\alpha I \\
&\quad + mn(n+m)K^3(k_1F_1T_{\mathrm{H}} - k_2F_2T_{\mathrm{L}})\}\big) \\
&\quad \big/\big(mk_1F_1\{[\alpha I(n-m) + K(m+n)](k_2F_2 + nK - n\alpha I)(\alpha IT_{\mathrm{H}} - 0.5I^2R + KT_{\mathrm{H}}) \\
&\quad - 0.5(m+n)KI^2R(k_2F_2 + nK - n\alpha I) - (nK)^2(\alpha I + K)T_{\mathrm{H}} \\
&\quad - K^2[k_2F_2(mT_{\mathrm{H}} + nT_{\mathrm{L}}) + mn(K - \alpha I)T_{\mathrm{H}}]\}\big),
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
\eta &= 1 - (nk_2F_2\{[\alpha I(n-m) + K(m+n)](k_1F_1 + mK + m\alpha I) \\
&\quad \times (\alpha IT_{\mathrm{L}} + 0.5I^2R - KT_{\mathrm{L}}) + 0.5(m+n)KI^2R(k_1F_1 + m\alpha I + mK) \\
&\quad + (mK)^2(K - \alpha I)T_{\mathrm{L}} + K^2[k_1F_1(mT_{\mathrm{H}} + nT_{\mathrm{L}}) + mn(K + \alpha I)T_{\mathrm{L}}]\}) \\
&\quad \big/\big(mk_1F_1\big\{[\alpha I(n-m) + K(m+n)](k_2F_2 + nK - n\alpha I)(\alpha IT_{\mathrm{H}} - 0.5I^2R + KT_{\mathrm{H}}) \\
&\quad - 0.5(m+n)KI^2R(k_2F_2 + nK - n\alpha I) - (nK)^2(\alpha I + K)T_{\mathrm{H}} \\
&\quad - K^2[k_2F_2(mT_{\mathrm{H}} + nT_{\mathrm{L}}) + mn(K - \alpha I)T_{\mathrm{H}}]\}\big).
\end{aligned} \tag{17}
$$

Eqs. (16) and (17) are the major results of this paper. They reflect the effects of heat transfers (k_1F_1 and k_2F_2), heat-reservoir temperatures (T_{H} and T_{L}), internal heat-conductance (K), internal electrical-resistance (R), Seebeck coefficient (α), working electric-current (I), number of thermoelectric-element pairs of the top stage (m), and number of thermoelectric-element pairs of the bottom stage (n) on the power output (P) and the thermal efficiency (η) of two-stage multi-element thermoelectric generator.

If $k_1F_1 = k_2F_2 \to \infty$, $T_1 = T_{\mathrm{H}}$ and $T_2 = T_{\mathrm{L}}$, Eqs. (16) and (17) become the results of conventional non-equilibrium thermodynamic analysis [19].

4. Performance optimization

Numerical calculations were performed in order to analyze and optimize the performance of the two-stage thermoelectric generator. In the calculation, $T_{\mathrm{H}} = 600$ K, $T_{\mathrm{L}} = 300$ K, $\alpha = 2.3 \times 10^{-4}$ V/K, $R = 1.4 \times 10^{-3}$ Ω m, $K = 1.5 \times 10^{-2}$ W m^{-1}/K, $k_1 = 60$ W/K, $k_2 = 15$ W/K and $F_{\mathrm{T}} = 0.07$ m^2 are set.

4.1. Optimum allocation of the number of thermoelectric-element pairs

Fig. 2 shows the effect of the number of thermoelectric-element pairs of the bottom stage (n) on the power output (P) versus the working electric-current (I) characteristic with $M = m + n = 40$. One can see from Fig. 2 that, for a fixed number of thermoelectric-element pairs of the bottom stage (n), the power output versus working electric-current characteristic behaves like a parabola, and there exists an optimum working electric-current $I_{P,n}$ which leads to an optimum power-output $P_{\mathrm{opt},n}$. If the number of thermoelectric-element pairs of the bottom stage (n) increases, both the optimum working electric-current $I_{P,n}$ and the corresponding optimum power-output $P_{\mathrm{opt},n}$ increase first and then decrease.

Therefore, the effect of the allocation of the numbers of the thermoelectric-element pairs between the top and bottom stages on the performance of the two-stage thermoelectric generator is obvious. Fig. 3 shows the effect of the total number of thermoelectric-element pairs of the two-stage thermoelectric generator (M) on the optimum power-output ($P_{\mathrm{opt},n}$) for the optimum working electric-current ($I_{P,n}$) versus the number of thermoelectric-element pairs of the bottom stage (n). One can see that, for a fixed M, there exist an optimum number of thermoelectric-element pairs for the bottom stage which leads to a maximum power-output ($P_{\max}$). With the increase of M, the maximum of the optimum power-output increases.

Fig. 4 shows the effect of the number of thermoelectric-element pairs of the bottom stage (n) on the thermal efficiency (η) versus working electric-current (I) characteristic with $M = m + n = 40$. One can see from Fig. 4 that, for a fixed number of thermoelectric-element pairs of the bottom stage (n), the thermal efficiency versus working electric-current characteristic behaves also like a parabola, and there exists an optimum working electric-current $I_{\eta,n}$ which leads to an optimum

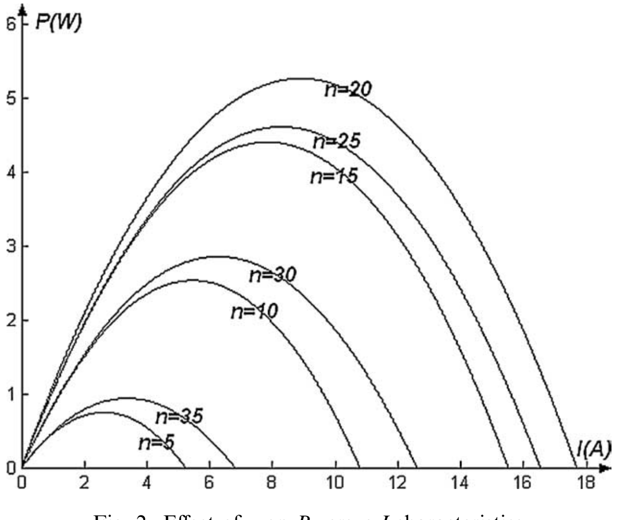

Fig. 2. Effect of n on P versus I characteristics.

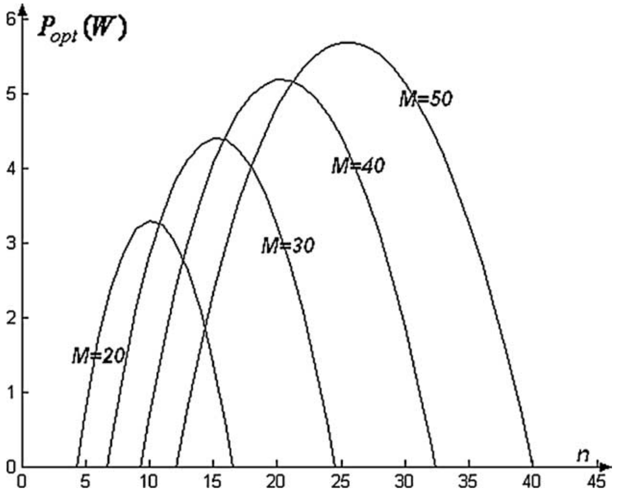

Fig. 3. Effect of M on P_{opt} versus n characteristics.

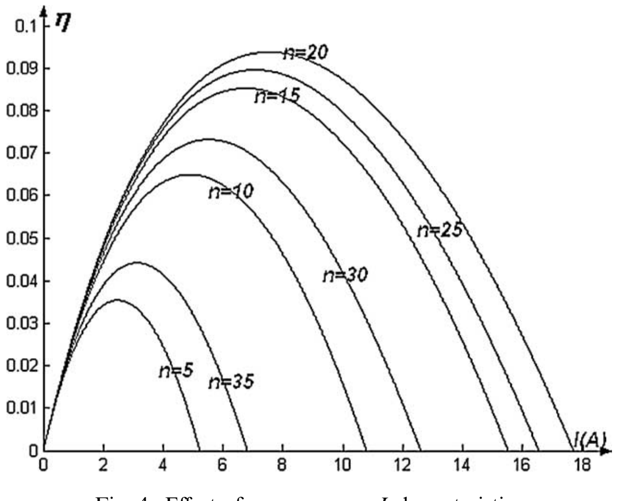

Fig. 4. Effect of n on η versus I characteristics.

thermal-efficiency $\eta_{\text{opt},n}$. If the number of thermoelectric-element pairs of the bottom stage (n) increases, both the optimum working electric-current $I_{\eta,n}$ and the corresponding optimum thermal efficiency $\eta_{\text{opt},n}$ increase initially and then decrease.

Fig. 5 shows the effect of the total number of thermoelectric-element pairs of the two-stage thermoelectric generator (M) on the optimum thermal-efficiency ($\eta_{\text{opt},n}$) for the optimum working electric-current ($I_{P,n}$) versus the number of thermoelectric-element pairs of the bottom stage (n). One can see that, for a fixed M, there exists an optimum number of thermoelectric-element pairs of the bottom stage which leads

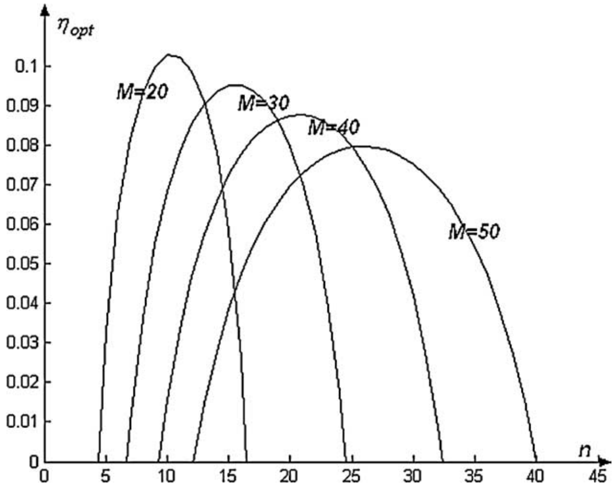

Fig. 5. Effect of M on η_{opt} versus n characteristics.

to a maximum optimum thermal-efficiency ($\eta_{\max}$). With the increase of M, the maximum of the optimum power-output decreases.

For the fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the top stage to the number of thermoelectric elements of the bottom stage ($x = m/n$) is optimized for maximizing the power output ($P_{\max}$) and thermal efficiency of the thermoelectric generator, respectively. Because both n and m are integers, the optimization is carried out by using an exhaustive search method. The optimum allocation of the number of the thermoelectric-element pairs between the top and bottom stages with different total numbers of the thermoelectric-element pairs of the generator is listed in Table 1. One can see that both the optimum allocation of the number of thermoelectric element pairs corresponding to the maximum optimum power output and the optimum allocation of the number of thermoelectric-element pairs corresponding to the maxima of optimum thermal efficiency are the same, and they are less than or equal to unity.

Table 1
Optimum allocation of the number of thermoelectric-element pairs

M	n	$P_{\max}$ (W)	$\eta_{\max}$	$x_{\text{opt}} = m/n$
50	26	5.677	0.080	24/26
43	22	5.363	0.085	21/22
40	20	5.180	0.086	20/20
35	18	4.828	0.091	17/18
30	15	4.395	0.095 (n = 16)	15/15
27	14	4.098	0.098	13/14
23	12	3.654	0.101	11/12
20	10	3.293	0.103	10/10

4.2. Optimum allocation of the heat-transfer surface-area

Eqs. (16) and (17) also can been used to optimize the allocation of heat-transfer surface of the heat-exchangers for the fixed total heat-transfer surface-area as has been accomplished for the conventional power-plants performed by Bejan [49–53] and others [54,55].

For the fixed total heat-transfer surface-area F_T of the hot- and cold-side heat-exchangers, that is, for the constraint of $F_T = F_1 + F_2$, defining the allocation of heat-transfer surface-area $f = F_1/F_T$ leads to

$$F_1 = fF_T, \quad F_2 = (1 - f)F_T. \tag{18}$$

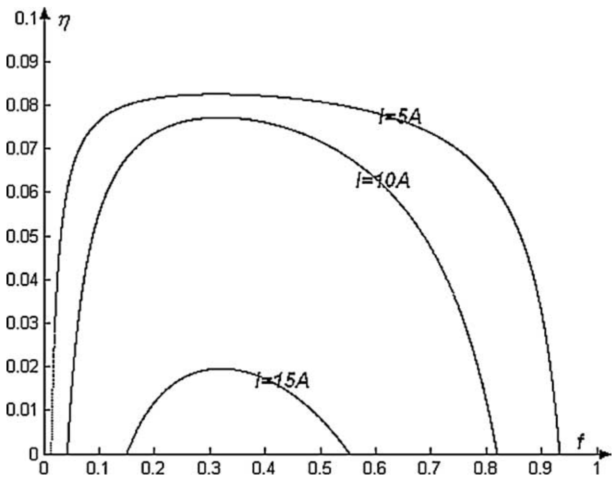

Fig. 6. Effect of I on P versus f characteristics.

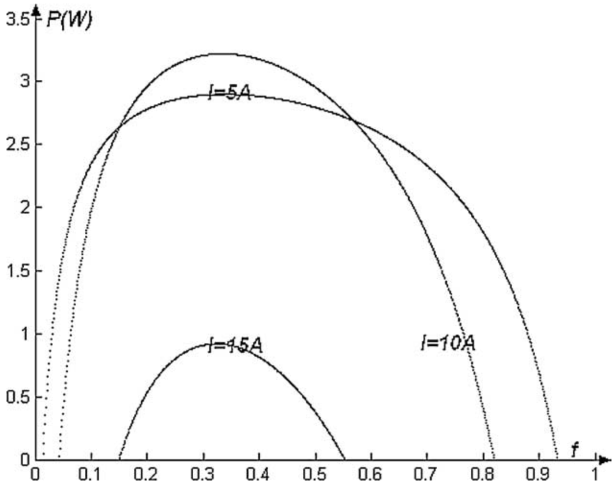

Fig. 7. Effect of I on η versus f characteristic.

Figs. 6 and 7 show the effects of the working electric-current on the power output (P) and the thermal efficiency (η) versus the allocation of heat-transfer surface-area (f) with $F_T = 0.07\ m^2$, $M = m + n = 40$ and $m = n = 20$. One can see that there exist one optimum allocation of the heat-transfer surface-area corresponding to the optimum power-output and another optimum allocation of the heat-transfer surface-area corresponding to optimum thermal-efficiency for the fixed working electric-current. In general, they are not equal to each other. Both the optimum allocations of the heat-transfer surface-area are insensitive to the value of the working electric-current.

5. Conclusion

A model of the performance of an internal and external irreversible two-stage thermoelectric generator is presented in this paper by using a combination of finite-time thermodynamics and non-equilibrium thermodynamics. The analytical formulae describing the power-output versus working electric-current, and the thermal efficiency versus working electric-current are derived. The performance optimization of the generator is performed by searching for the optimum allocation of heat-transfer surface-area of the high- and low- temperature side heat-exchangers and the optimum allocation of the number of thermoelectric-element pairs based on the maximization of the working electric-current. All the parameters should be considered in the design and application of practical thermoelectric-generators in order to obtain the maximum economic benefit. The results obtained herein may provide guides for the design and application of practical thermoelectric-generators.

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